Orientation of Galaxies in the Local Supercluster: A Review

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Abstract

The progress of the studies on the orientation of galaxies in the Local Supercluster (LSC) is reviewed and a summary of recent results is given. Following a brief introduction of the LSC, we describe the results of early studies based on two-dimensional analysis, which were mostly not conclusive. We describe next the three-dimensional analysis, which is used widely today. Difficulties and systematic effects are explained and the importance of selection effects is described. Then, results based on the new method and modern databases are given, which are summarized as follows. When the LSC is seen as a whole, galaxy planes tend to align perpendicular to the LSC plane with lenticulars showing the most pronounced tendency. Projections onto the LSC plane of the spin vectors of Virgo cluster member galaxies, and to some extent, those of the total LSC galaxies, tend to point to the Virgo cluster center. This tendency is more pronounced for lenticulars than for spirals. It is suggested that 'field' galaxies, i.e., those which do not belong to groups with more than three members, may be better objects than other galaxies to probe the information at the early epoch of the LSC formation through the analysis of galaxy orientations. Field lenticulars show a pronounced anisotropic distribution of spin vectors in the sense that they lay their spin vectors parallel to the LSC plane while field spirals show an isotropic spin-vector distribution.
Key words: Local Supercluster, orientation, spin vectors, anisotropy

1 Introduction

Superclusters are the largest structure in the Universe with scales up to $\sim$100–150 Mpc. They are in largely unrelaxed state. At a typical velocity of $\sim$1000 km s^{-1}, galaxies can move only $\sim$10 h^{-1}Mpc within the Hubble time (Hubble constant H_0=100h km s^{-1} Mpc^{-1}). Accordingly, the superclusters seen today tell us the condition of the Universe when these largest structures were formed (Oort, 1983; Bahcall, 1988). The dynamical 'fossil' nature of the alignment of rotational axes of galaxies in superclusters provides us with the information on the formation process of galaxies at the early epoch (Djorgovski, 1987).

The orientation of galaxies in the Local Supercluster (hereafter LSC) has been studied extensively by many investigators (e.g., Reinhardt and Roberts, 1972; Jaaniste and Saar, 1977, 1978; Kapranidis and Sullivan, 1983 (hereafter KS); MacGillivray et al., 1982; MacGillivray and Dodd,

1985a,b; Flin and Godlowski, 1986 (hereafter FG); Kashikawa and Okamura, 1992 (hereafter KO); Godlowski, 1993, 1994; Garrido et al., 1993; Han et al., 1995; Sugai and Iye 1995; Yuan et al., 1997; Hu et al., 1998; Aryal and Saurer, 2001a, 2005c). However, the results of these studies are quite uncertain, and some of them are even in contradiction with each other. Some authors found that the galaxy planes tend to be parallel to the LSC plane, while others found no strong tendency of alignment, or even showed that galaxy planes tend to be perpendicular to the LSC plane.

In this paper we attempt to clarify the cause of the uncertainty and summarize what we have learned on the orientation of galaxies in the LSC. We will put our primary emphasis on disk galaxies, i.e., spirals and lenticulars, and the global features of galaxy alignment of the LSC as a whole. This is because disk galaxies are rotationally supported, and their spin vectors are the dynamical parameter related to the formation processes at early epoch, and the global features of galaxy alignments of the LSC will shed some light on the origin and formation of the LSC. Discussion of the results of many studies on the orientation of galaxies in other groups, clusters, and superclusters (e.g., Dojorgovski, 1987; Han et al. 1995; Cabanela and Aldering, 1998; Fuller et al., 1999; Flin, 2001; Aryal and Saurer, 2001b, 2004b, 2005a, b; Bukhari and Cram 2003, etc.) is beyond the scope of this paper.

We start in section 2 with a brief introduction of the LSC. Early studies are reviewed in section 3. The new three-dimensional analysis and the statistical methods used are described in section 4. Early results from the three-dimensional method are summarized in section 5. Difficulties and systematic effects are discussed in section 6. The results obtained with the new method applied to disk galaxies selected from modern databases are described in section 7. Finally, a summary and prospects are given in section 8.

2   The Local Supercluster

The earliest recognition of the LSC dates back to the William and John Hershel's work, who showed an excess of bright nebulae in the northern galactic hemisphere (Herschel, 1784, 1785, 1802, 1811). More recent evidence for its existence was given by Reynolds and Lundmark in 1920's (e.g., Lundmark, 1927), Holmberg (1937) and G. de Vaucouleurs (1953, 1956, 1958, 1960, 1978, 1981).

De Vaucouleurs was the first who presented the firm observational evidence for the LSC. He pointed out that the aggregation of the brightest galaxies in the northern galactic hemisphere which extends along the great circle is a flat super-system (Supergalaxy) with the axial ratio about 5:1 centered on the Virgo Cluster. He also defined some fundamental parameters of the LSC. The position of the supergalactic pole is defined as $\alpha(1950)=18^h 52.^m 8$, $\delta(1950)=+15°38'$. Supergalactic coordinates (L and B) are introduced by de Vaucouleurs et al. (1976) (see also MacGillivray et. al., 1982). The center of the Local Supercluster is in the direction of the Virgo Cluster, $\alpha(1950)=12^h 28^m$, $\delta(1950)=+12°40'$, and its distance is D $=15$ Mpc (de Vaucouleurs, 1982). The position of the Virgo Cluster is in the direction of L=103°, and B=−2°. A review paper of the LSC was presented at the IAU Symposium No.79 (de Vaucouleurs, 1978).

A detailed description of the global structure of the LSC based on galaxy space coordinates, derived from their radial velocities, can be found in Yahil et al. (1980), Oort (1983), Tully (1982, 1988) and the references therein. With the present knowledge, about one-third of the mass of the LSC resides in the halo component and the remaining two-thirds are in the disk component, with about a half of its mass contributed by the Virgo cluster. About 70% of nearby galaxies belong to groups or clusters within the LSC if the Virgo members are included.

Some catalogs relevant to the LSC include:

- The Shapley and Ames Catalog (hereafter SA)
  A catalog of 1249 galaxies brighter than 13.0 photographic magnitude published by Shapley and Ames (1932) based on the Harvard photographic survey. They revealed the existence of the "Super-galactic Equator" (see also Oort, 1983), which is the aggregation of bright galaxies along the great circle that passes through the Virgo Cluster, the core of the LSC as we know now.

- The Revised Shapley and Ames Catalog of Bright Galaxies (hereafter RSA)
  A revised catalog of SA published by Sandage and Tammann (1981, 1987), which contains

magnitudes, morphological types, and redshifts of 1246 galaxies in the SA. This is the first catalog that gives galaxy *distances* based on the redshift and a Virgo infall model.

- The Nearby Galaxies Catalogue (hereafter NBG)
  A catalog of 2367 galaxies with velocities smaller than 3000 km s^{-1} as of 1978 (Tully 1988). Among the 2367 galaxies, 1053 belong to RSA and 1515 come from all sky HI survey by the author and collaborators. NBG is a companion to the Nearby Galaxies Atlas (Tully and Fisher, 1987).

- Photometric Atlas of Northern Bright Galaxies (hereafter PANBG).
  A uniform detailed surface photometry database of 791 galaxies in the northern hemisphere selected from the RSA published by Kodaira et al. (1990). It contains photometry parameters, isophotal contours, and luminosity profiles measured in the V band.

3   Early Studies Based on Two-Dimensional Analysis

The study of galaxy orientation in the LSC can be traced back to long time ago (e.g., Reynolds, 1920, 1922, Holmberg, 1937; Danver, 1942; Brown, 1938, 1939, 1964, 1968; Thompson, 1973; see also Hawley and Peebles, 1975 and references therein). The advent of the Uppsala General Catalogue of Galaxies (Nilson, 1973; hereafter UGC) and the ESO/Uppsala Survey of the ESO(B) Atlas (Lauberts, 1982; hereafter ESO/U), which give the position angles for thousands of galaxies, stimulated the research in this field.

Results of earliest studies were inconclusive. Reynolds (1920, 1922) showed that if the shape of spiral galaxies is approximated by a thin disk, there is an excess of large spirals at small inclination angles to the line of sight. Using 593 galaxies with diameters greater than $2'$ in the catalog of Herschel nebulae, Brown (1938) found an apparent large excess of small inclinations (estimated by axial ratios b/a) to the line of sight, which he believed to be a real phenomenon due to a systematic orientation of galaxy planes in space.

From the analyses of distribution of position angles of galaxies in Shapley's catalog of 7889 external galaxies in Horologium and surrounding regions and SA, Brown (1939, 1964, 1968) found evidence for anisotropy in the orientation in some sky regions, while Reaves (1958) found no such effect by measuring position angles of galaxies on the two plates which cover in part the region of the Shapley's survey. Kristian (1967) was also unable to find anisotropy. Hawley and Peebles (1975) measured orientations of 5559 galaxies in three sky areas on the Palomar Observatory Sky Survey (hereafter POSS) red plates and found no significant deviation from anisotropy.

The results of later studies did not improve the situation very much. Reinhardt and Roberts (1972) studied the mean apparent ellipticity of galaxies in the Reference Catalogue of Bright Galaxies (de Vaucouleurs and de Vaucouleurs, 1964, hereafter RC1) and concluded that orientations of the spin vectors (hereafter SVs) of the galaxies are preferentially perpendicular to the LSC plane. From a study of 1027 galaxies within 25 Mpc (radial velocity $V < 2500$ km s^{-1} or $m < 12.5$) in RC1 and UGC, Jaaniste and Saar (1977) found the opposite trend with the spin vectors parallel to the LSC plane. In 1953-54, de Vaucouleurs studied the position angles of galaxies close to the supergalactic equator in the catalog by Reinmuth (1926) and examined the distribution of the poles of the 200 large spirals in the catalog by Danver (1942). De Vaucouleurs (1981) claimed in an abstract that this unpublished research failed to detect any strong tendency of the galaxy planes to be parallel, i.e. the SVs were perpendicular, to the LSC plane. MacGillivray et al. (1982) analyzed the distribution of the position angles and ellipticities of 727 spirals and irregulars with $B_T < 13.0$ mag. and radial velocity corrected for solar motion $V_0 < 2500$ km s^{-1} in the Second Reference Catalogue of Bright Galaxies (de Vaucouleurs, G. et al., 1976; hereafter RC2) and the UGC. They found that galaxies belonging to the LSC have a slightly non-random distribution of their SVs. The SVs tend to be perpendicular to the LSC plane. This trend is most pronounced for galaxies at high supergalactic latitude and those seen nearly edge-on.

In summary, the results of these early studies were inconsistent, and at times even in contradiction with each other. Some authors concluded that the galaxy planes tend to be parallel to the LSC plane, i.e. their SVs are perpendicular to the LSC plane (e.g., Reinhardt and Roberdts 1972; MacGillivray et al. 1982). On the other hand, others concluded that galaxy planes tend to be

perpendicular to the LSC plane, i.e. their SVs are parallel to the LSC plane (e.g., Jaaniste and Saar, 1977, 1978). Finally, some authors found no strong tendency of alignment at all (e.g., KS). Possible causes for these inconsistencies include probably different data sampling, large errors in the data, selection effects, background contamination, and incompleteness of the sample, etc.

It might be worthwhile to mention a possible evolutionary effect on the galaxy orientation. Using the III_aJ plates taken with the UK 1.2 m Schmidt Telescope, MacGillivray and Dodd (1985b) examined the position angle distribution of galaxies in a magnitude-limited sample down to $B{=}16$ mag in the Virgo region (25 square degrees). They did not find a global effect of alignment of Virgo galaxies along the LSC plane. However, the galaxies did show a strong alignment in the sense that the galaxy planes are preferentially oriented perpendicular to the radius vector to NGC 4406 near the Virgo center. They concluded that this perpendicularity is unlikely to be a primordial effect. The most likely cause is a dynamical effect in the post-formation epoch, such as rotation around the Virgo center, infall to the center, or tidal interaction between galaxies and the massive cluster core. Using a new method and a new database (see below), KO found a similar effect. They concluded that the projections on the LSC plane of the SV of the galaxies in the core and the vicinity of the Virgo cluster tend to point towards the Virgo center. This effect was also confirmed by Hu et al. (1995; hereafter HWSL).

The method generally used in early studies was to look for anisotropy in the distributions of position angles PA and/or axial ratios b/a of galaxy images. The position angle distribution and the axial ratio distribution were examined *independently*. It was merely a two dimensional analysis in nature which deals only with the projection of galaxies on the sky. Since we are inside the LSC, the projected shapes of galaxies look different depending on the direction and the distance from us. Therefore, if any alignment of SVs in the three dimensional space exists it may be diluted by this projection effect.

4   Three-Dimensional Analysis and Statistical Tests

A three-dimensional analysis, which analyzes position angles and axial ratios of galaxies *simultaneously*, was introduced as a new method in late 70's (Jaaniste and Saar, 1977, 1978; KS; FG).

Before we describe this method frequently applied now, we will clarify first the coordinate system in which spatial orientation and distribution of the galaxies of LSC can be specified. The position of a galaxy is expressed in terms of the supergalactic polar coordinates (L, B, distance) or the supergalactic Cartesian coordinates (SGX, SGY, SGZ). The latter was introduced by Tully (1982). The SGZ axis was defined to point to the direction B=+90 °; the SGX axis was aligned toward L=0 °, B=0°; and the SGY axis was aligned toward L=90°, B=0°. In the supergalactic Cartesian coordinate system defined above, the SGX-SGZ plane is almost coincident with the plane of the Galaxy; the positive SGY axis is only 6° off the north Galactic pole. The direction of the Virgo cluster center is close to the SGY axis (offset by 13°).

To specify the orientation of the SV of a galaxy, two angles are defined. The angle θ is the polar angle between the SV and the LSC plane, and the angle ϕ is the azimuthal angle between the projection on the LSC plane of the SV and the SGX axis. A schematic illustration of angles θ and ϕ is shown in Fig. 1, which is taken from KO. In FG and some other papers (e.g. Hu et al., 1998), the basic great circle 'Meridian' of the supergalactic system is selected to go through the center of the Virgo cluster: $\alpha = 186.°25$, and $\delta = +13.°10$ (Sandage and Tammann, 1976).

The required observational data are the position angle PA and the axial ratio b/a of a galaxy. The inclination angle i of the galaxy can be derived from the observed axial ratio b/a and the intrinsic flatness, i.e., true axial ratio q_0, which is dependent on the morphological type. The values of q_0 for different types can be taken from Heidmann, Heidmann and de Vaucouleurs (1971) or Bottineli, Gouguenheim, Paturel, and de Vaucouleurs (1983). It is sometimes assumed that q_0 is constant, say 0.2 (Holmberg, 1958; Tully, 1988), for disk galaxies of all types. Through the PA and i, the spatial orientation of the SV of a galaxy is specified by angles θ and ϕ.

In practice, the transformation of galaxy position between the equatorial and supergalactic coordinate systems should be established first. Based on the position angle measured with respect to the equatorial coordinate system p, the position angle with respect to the supergalactic coordinate system PA can be obtained (MacGillivray et al., 1982; KO). The angles θ and ϕ that specify the

SV orientation of the galaxy can be derived from the following formulae given by FG and KO:

$$\sin \theta = -\cos i \sin B \pm \sin i \cos q \cos B, \tag{1}$$

$$\sin \phi = (\cos \theta)^{-1} \left[-\cos i \cos B \sin L + \sin i \left(\mp \cos q \sin B \sin L \pm \sin q \cos L \right) \right], \tag{2}$$

where i is the inclination angle estimated from the axial ratio by

$$\cos^2 i = [(b/a)^2 - q_0^2]/(1 - q_0^2), \tag{3}$$

which is valid for oblate spheroids (Holmberg, 1946). The angle q is defined as $q = PA - \pi/2$.

There is one limitation in this analysis. As KO pointed out, there are four solutions for the orientation of the SV of a galaxy with a given position angle and a given axial ratio. This ambiguity is caused by the fact that we do not know which side of the galaxy is closer to us, and whether the spin axis is pointing towards or away from us. Usually all these four possibilities are counted as independent entries.

With the optical image and HI velocity fields, it is possible to solve the ambiguity and therefore determine the orientation of the SV of a galaxy uniquely. By using the HI velocity field, we can decide which side of a galaxy is approaching towards us. The optical image can tell us the direction of the SV if we assume that spiral arms are trailing. Helou and Salpeter (1982) and Hoffman et al. (1989) examined the orientations of the SV of Virgo galaxies by this method. Unfortunately, however, the available sample was too small to derive a firm conclusion. Cabanela and Dickey (1999) used HI observations with Arecibo telescope to determine the SVs of galaxies in the Pisces-Perseus supercluster. Based on the analysis of the SVs of 54 nearly edge-on galaxies, they found no significant evidence for alignment. The sample size of this study is, however, also not large enough.

We give below a brief introduction on the statistical methods used to evaluate whether the observed SV distribution is isotropic or not. There are several kinds of statistical tests. Here we discuss the chi-square (χ^2) test and the Kolmogorov-Smirnov test (hereafter K-S test), which are commonly used. Some other statistical tests, say, the Fourier test and the autocorrelation test, were also used and discussed in detail by FG and Godlowski (1993, 1994).

1) The χ^2 test

The χ^2 test is an objective way to estimate the goodness of the fit (e.g., to the isotropic distribution) based on the reduced chi-square value, χ^2_ν, which is defined by

$$\chi^2_\nu = \frac{1}{\nu}\chi^2 = \frac{1}{\nu}\sum_{i=1}^{n} \frac{(N_{oi} - N_{ei})^2}{N_{ei}}, \tag{4}$$

where n is the number of bins, $\nu = n - 1$ is the degree of freedom, and N_{oi} and N_{ei} represent the observed and expected (isotropic) values in the ith bin, respectively. The quantity $P(> \chi^2_\nu)$ defined by

$$P(> \chi^2_\nu) = 1 - [2^{\nu/2}\Gamma(\nu/2)]^{-1} \int_0^{\chi^2} e^{-\frac{t}{2}} t^{\frac{\nu}{2}-1} dt, \tag{5}$$

and gives the probability that the observed distribution is realized from the isotropic distribution. The observed distribution is more consistent with the isotropic distribution when $P(> \chi^2_\nu)$ is larger. For the isotropic distribution, the $P(> \chi^2_\nu)$ value is expected to be nearly 1. The critical value $P(> \chi^2_\nu) = 0.05(5\%)$ is often set to discriminate between isotropy and anisotropy, which corresponds to the significance at 2σ level. Usually $10°$ is adopted as the bin size for the observed θ and ϕ distributions.

There is a limitation for the χ^2 test that data must be binned, and therefore some information may be lost by binning. The K-S test, which can be applied without any binning, does not suffer from this disadvantage.

2) K-S test

Let the cumulative distribution function of an observed sample $(x_1, x_2, ..., x_n)$ be $S_n(x)$, and the known theoretical (e.g., isotropic) one be $P(x)$. K-S test is based on the maximum absolute difference between these two cumulative distribution functions defined by

$$d = \max_{-\infty < x < +\infty} |S_n(x) - P(x)|. \tag{6}$$

The probability α that $S_n(x)$ deviates from $P(x)$ is approximated by

$$\alpha(> d) = Q_{KS}([\sqrt{n} + 0.12 + 0.11/\sqrt{n}]d), \tag{7}$$

where

$$Q_{KS}(\lambda) = 2 \sum_{j=1}^{\infty} (-1)^{j-1} e^{-2j^2\lambda^2}. \tag{8}$$

Q_{KS} is a monotonic function with the limiting values: $Q_{KS}(0) = 1$, $Q_{KS}(\infty) = 0$. The observed sample does not follow the theoretical distribution function $P(x)$ when $\alpha(> d)$ is very small. Since it is a test to examine whether or not two distributions are drawn from the same population, the K-S test can be used to judge whether the SV distributions of spirals and lenticulars follow the same distribution function or not as well as to judge the isotropy.

The SV's polar angle θ ranges from $0°$ to $90°$, and the azimuthal angle ϕ from $-90°$ to $90°$. For the isotropic SV distribution, the expected cumulative distribution functions are

$$P(\theta) = \int_0^{2\pi} \int_0^{\theta} r^2 cos\theta d\theta d\phi / \int_0^{2\pi} \int_0^{\pi/2} r^2 cos\theta d\theta d\phi = sin\theta, \tag{9}$$

and

$$P(\phi) = \frac{1}{2} + \frac{\phi}{\pi}, \tag{10}$$

respectively.

5 Early Results from the Three-Dimensional Analysis

KS analyzed various samples of spiral galaxies of the LSC from UGC ranging in size from 425 to 1154 and found no strong tendency of alignment. However, their high-latitude sample No.2 (702 galaxies with Zwicky magnitude $m_z \leq 14.0$ and $|B| > 10°$) showed a marginal sign that galaxy planes align parallel to the LSC plane (2σ-effect).

On the other hand, FG analyzed the data of 1275 galaxies in UGC which have radial velocities smaller than 2600 km s^{-1} corrected for solar motion. Following Hawley and Peebles (1975), FG used three statistical methods, which are the χ^2 test, the Fourier test, and the autocorrelation test. The value 45 ° was defined as the boundary between the direction parallel to and that perpendicular to the LSC plane. FG found a tendency that galaxy planes align perpendicular to the LSC plane, which is observed mostly for face-on galaxies whose distribution is different from that of edge-on galaxies. They also found a weak tendency that the projection of SVs of galaxies onto the LSC plane tend to point to the Virgo center. Due to the lack of data, KS and FG both assumed 0° for the position angle of face-on galaxies. FG argued that (1) a significant fraction of non-LSC members are present in KS's sample No.2 and that (2) the marginal tendency seen in KS's sample No.1 (425 galaxies with galactocentric redshift $V_0 < 2500$ km s^{-1}), which KS did not regard as significant, is consistent with their finding that galaxy planes align perpendicular to the LSC plane.

Flin and Godlowski (1989) and Godlowski (1993, 1994) analyzed a sample of 2227 galaxies taken from UGC and ESO/U, in both northern and southern hemispheres, which have radial velocities smaller than 2600 km s^{-1} corrected for solar motion and another sample from NBG. They found that the distribution of galaxy planes throughout the LSC is anisotropic; planes tend to align perpendicular to the LSC plane. They also found that SVs of galaxies projected on the LSC plane show a tendency to point to the center of the Virgo cluster. These effects were shown to be more pronounced for the 'non-spiral' galaxies (all types other than spirals and lenticulars) than for the 'spiral' galaxies (lenticulars and spirals). Figure 2 is taken from Godlowski (1994), which shows the observed (solid line) and the theoretical isotropic (dashed line) distribution of the angle $\delta(= \theta$ in this paper) (a), and angle η (=ϕ in this paper) (b), for the whole sample of galaxies. Flin and Godlowski (1989) concluded that the parallelism of galactic planes to the LSC plane found previously by some authors was due to the exclusion from the analysis of face-on galaxies whose PA is difficult to be determined.

Godlowski (1994) found that galaxy alignments strongly dependent on supergalactic coordinates, radial velocity distance and galaxy structure. Planes of galaxies with small $|SGB|$ (at low

supergalactic latitudes) tend to be perpendicular to the LSC plane while planes of galaxies with large $|SGB|$ (at high supergalactic latitude) tend to be parallel to the LSC plane. He claimed that the detected perpendicularity of galactic planes to the LSC plane might be caused by the perpendicularity of the galactic planes to the radius vector pointing to the LSC center.

Parnovsky et al. (1994) analyzed edge-on galaxies in UGC, ESO/U, and their own catalog (Karachentsev et al., 1993) and detected a statistically significant anisotropy of galaxy orientations with an excess of projected SVs pointing to the region $4^h < \alpha < 6^h$ and $+20° < \delta < +40°$. Not all the sample galaxies had redshift information and they claimed that the observed anisotropy is global over the scale of 100-200 Mpc, based on the analysis of apparent size of galaxies. However, Flin (1995) indicated that this anisotropy is due to the LSC.

It is mentioned here that the three-dimensional method, when face-on galaxies are included in the analysis, began to give a consistent result that the planes of LSC galaxies tend to align perpendicular to the LSC plane and that SVs of galaxies projected on the LSC plane tend to point to the center of the Virgo cluster. (e.g., FG, Goldlowski, 1993, 1994, Flin 1996). However, there are two issues of concern which should be mentioned. First, majority of the studies mentioned above used 'all galaxies' as sample galaxies, i.e., ellipticals, lenticulars, spirals, irregulars and others. Second, most of the studies after 1973 used the UGC data, which are now known to suffer from selection effects. In the next section we give a discussion about technical problems related to these issues, i.e., difficulties and systematic effects encountered in determining galaxy orientations.

6   Difficulties and Systematic Effects in Studying Galaxy Alignment

6.1   Position Angle and Axial Ratio

(a) Selection Effect of UGC

There are many factors that can affect the determination of position angle PA and axial ratio b/a. We discuss first the selection effects in the UGC, since most studies after 1973 used this catalogue.

The UGC catalog was compiled by visually inspecting the galaxies larger than 1 arcmin on the POSS blue and red prints. The position angles and axes of galaxies were measured by eye. As it is more difficult to measure PA for rounder galaxies, this leads to larger errors of PA for rounder galaxies. For the face-on galaxies the position angles are not given in the UGC.

KO compared PA and b/a of 387 galaxies cataloged in UGC with those given in PANBG. The result is shown in Fig. 3. The average difference, standard deviation and maximum difference of b/a and PA between the two sets were computed. The values are 0.06(7.5%), 0.07, and 0.54(67.5%) in b/a, and 7.2°(8.0%), 15.6°, and 80.0°(88.9%) in PA. They found that for both b/a and PA the difference increases for more face-on galaxies. KO also found that most of 71 galaxies cataloged in the UGC with measured diameters but without PA are face-on galaxies. They concluded that the selection effect against face-on galaxies in the UGC is too large for them to be included in analyses that make use of b/a and PA.

Hu et al. (1993) and HWSL also discussed selection effects in the UGC (see Fig. 4) based on their analysis of 310 disk galaxies in the Virgo area, which will be discussed in more detail in section 7.2. They found that UGC galaxies with PA preferentially have high inclination angles i; 90% of them have $i > 40°$, and no galaxies with PA are found for $i < 20°$. They also found that the number of UGC galaxies with b/a but without PA is about 20% of the total, of which about 80 % have $i < 40°$. The remaining 20% (i.e., 13 galaxies) with i between 40° and 70° are found to be mostly faint Sm/Im galaxies and peculiars, i.e., 4 Sm, 6 Im, 1 Imp and 1 Sp with B_T between 14.0 and 18.1 mag., except one bright S0p (Hu et al. 1993; HWSL). Thus, they concluded that in addition to the selection effect against nearly face-on galaxies, a second morphology-dependent selection effect against faint galaxies with irregular shapes is present in the UGC. This indicates that incompleteness increases as a galaxy sample goes fainter, particularly for those galaxies with irregular shapes like Sm, Im and peculiars.

Most studies based on UGC galaxies either did not include face-on galaxies without PA given in the catalog. Others simply assumed some certain values for the PA of those galaxies. For example,

KS and FG assumed $PA = 0°$, and Godlowski (1994) and HWSL assigned by computer simulation random values to supergalactic PA or PA. KS claimed that assigning $PA = 0$ leads to errors of $\leq 30°$ in the PA of the($\sim$20%) face-on galaxies in their sample. When surface photometry is available, PA and b/a are determined usually by a least squares fit of an ellipse to the isophote at a certain surface brightness level, e.g., 25 mag arcsec^{-2} as in PANBG. The internal accuracy of the PANBG data were estimated as, $\sigma(PA_{25}) \sim 4.5°$ (only for galaxies with $b/a < 0.8$), $\sigma(\log a_{25}) = 0.03$, and $\sigma(b_{25}/a_{25}) = 0.04$ (PANBG). By using the data measured by surface photometry, the face-on problem could be mitigated. However, the isophotes of galaxies with irregular shapes are not well fitted by an ellipse. KO found 31 galaxies ($\sim 5\%$ of their total sample) seems to have large errors, but they claimed that their results were not affected by this.

(b) Effects of Measurement Errors and Other Uncertainties

In this section we discuss the effects resulting from the errors in the data and some approximation treatments. Firstly, there is the Holmberg effect: a systematic difference between diameters and axial ratios visually measured on photographic plates, and those measured using photometer tracings or surface photometry (Holmberg 1975). One must take this effect into account when one uses visually estimated diameters and axis ratios. One way to do so is to define a system of standard diameters from photometric measurements, and to reduce other visual measurements to the system. Fouqué and Paturel (1985) presented an improved standard system of 250 galaxies based on the catalog of 237 standard photometric diameters (Fouqué and Paturel, 1983). They presented the formulae to convert the visual diameters of galaxies given in large catalogs (ESO, UGC and MCG) to this system.

FG examined the effect of random errors of the order of $0.1'$ in both a and b, and those of $5°$ in PA. They obtained quite similar results when these errors are introduced independently or simultaneously. Flin (1989) also analyzed the influence of errors in PA and b/a. He pointed out that errors of $\Delta(b/a) = 0.1$ and $\Delta PA = 13°$, combined with the flatness of the LSC, did not give rise to spurious anisotropy. Flin and Godlowski (1989) took into account random errors of $\sim 0.1'$ in a and b and $\sim 5°$ in PA for all samples, and assumed a random distribution for PA or inclination angle i for face-on galaxies. These authors found that the observed effect did not change the results qualitatively, although a quantitative difference did appear. FG and Godlowski (1993) concluded that the supergalactic PA of face-on galaxies are distributed essentially random. Godlowski (1994) claimed that angles θ and ϕ of face-on galaxies depend only weakly on the supergalactic PA. Based on their previous researches, Godlowski (1994) claimed that assigning a random distribution to the supergalactic PAs of face-on galaxies would be a good approximation.

There are more factors which can affect the measurement accuracy, even if the data are derived from surface photometry. For example, poor seeing makes the elongated image of galaxies rounder, i.e, makes b/a larger. Other effects which lead to non-circular images such as telescope tracking error and PSF anisotropy also affect b/a and PA. However, all these effects usually do not exceed a few arcsecs and are negligible for bright galaxies in the LSC discussed here. For example, the limiting diameters of galaxies of the samples discussed here are of the order of 1 arcmin; $1.'0$ (UGC), $0.'9$ (ESO/U), and $1.'7$ (FGCP discussed in section 7.2; Fouqué et al., 1992). A random sampling showed that the typical value of diameters of the PANBG galaxies with velocity smaller than 3000 km s^{-1} and brightness near 13 mag is also about $1.'0$ ($0.'8 - 1.'3$). However, we must be aware that these effects can become important when we analyze smaller and/or fainter galaxies in the LSC or distant galaxies outside of the LSC.

6.2   Inclination Angle

Inclination angle i can be derived from equation (3), which is valid for oblate spheroids. It is generally believed that disk galaxies are fast rotating oblate objects and that their rotation axes are normal to their disk planes. It is thus reasonable to use equation (3) for disk galaxies.

On the other hand, intrinsic shape and rotation of elliptical galaxies are more complex. The twist of PA observed in many elliptical galaxies suggests that they do not possess an axis of rotational symmetry, but are triaxial objects (Mihalas and Binney, 1981; Binney and Tremaine, 1987, and references therein). Some ellipticals may be prolate spheroids rather than oblate spheroids. It is hard to define a meaningful plane and an axis of rotating symmetry (i.e., a SV) for triaxial objects.

Furthermore, most bright ellipticals are known to be slow rotators (Illingworth, 1977, Davies et al., 1983; Binney and Tremaine, 1987; Binney and Merrifield, 1998 and references therein). The origin of rotation of ellipticals may be different from that of disk galaxies. When ellipticals were included in the analysis in previous studies, their inclination angles were estimated by equation (3) in the same manner as disk galaxies. Considering the complexities arising from intrinsic shape and slow rotation, we recommend not to use elliptical galaxies in the analysis of SVs.

For disk galaxies, the inclination angle i is derived from the observed b/a and intrinsic axial ratio q_0 through equation (3). The observed values of b/a were sometimes converted to a standard, photometric axial ratio using the formula given by Fouqué and Paturel (1985) (e.g. Flin and Godlowski, 1989; Godlowski, 1994). Flin and Godlowski (1989) discussed the Holmberg effect using their 2227 UGC and ESO/U galaxies. They considered various cases; $q_0 = 0$, and $q_0 \neq 0$ with and without the Holmberg effect taken into account. They found the following: Neglecting the Holmberg effect results in a greater anisotropy than that when it is allowed for. The smallest anisotropy is found when $q_0 \neq 0$ and the Holmberg effect is neglected. However, the coefficients that characterize the deviation from isotropy do not change significantly among all the cases. Using 1275 UGC galaxies, FG also showed that the differences with or without accounting for the Holmberg effect (for $q_0 \neq 0$) were statistically negligible.

6.3   Selection Effects on Galaxy Position and Inclination Angle

Using simulations including 2×10^5 virtual galaxies, Aryal and Saurer (2000) computed the distribution of polar and azimuthal angles of galaxy rotation axes expected for the isotropic distribution. They showed that the selection effects concerning positions and inclination angle i of galaxies may play an important role when samples are incomplete (e.g. limited sky coverage) (see Fig.5 below). They also pointed out that up to now no authors have used homogeneous data covering both the northern and southern hemisphere for their studies on SVs of galaxies: FG mainly used the UGC data; Goldlowski (1993, 1994) added the data from ESO/U; KO, Yuan et al. (1997), and HYWSL used the PANBG galaxies with $\delta > -25°$. The correct treatment of face-on galaxies is also a crucial point when studying galaxy alignment.

Aryal and Saurer (2000) showed that the expected isotropic distribution curve is cosine for the polar angle θ and a straight line for the azimuthal angle ϕ *only when* there is no selection effect in (L, B), supergalactic position angle PA and inclination angle i. Their main conclusions on selection effects are as follows: 1, The θ distribution deviates from the cosine curve when some selection effect is present in the axis ratios, i.e., inclination angles i. The way of deviations is dependent on B. 2, The distribution of ϕ is very much affected by selection effects. Even if there is no selection effects on B and i, selection effects on L make the distribution deviate from the expected straight line. Selection effects on i also change the ϕ distribution diffferently for different ranges of L.

As an example, we show in Fig. 5 the difference between the expected isotropic distribution calculated by Aryal and Saurer (2000) as solid lines and the usually adopted one under the assumption of no selection effect with dashed lines, for the θ distributions of the member galaxies of the Virgo cluster (HWSL) and for the ϕ distributions of the field galaxies (HYSWL). These authors claimed that since the selection effects on the position and the inclination angle are present in all available databases, proper simulations should be made to interpret the results.

7   The Results from Disk Galaxies

In this section we will concentrate on galaxy alignments of disk galaxies, i.e., spirals and lenticulars obtained from modern databases.

7.1   New database: Photometric Atlas of Northern Bright Galaxies, and KO's study

A new database PANBG became available in 1990, which is based on homogeneous surface photometry of galaxies observed with the 105 cm Schmidt telescope at Kiso Observatory. PANBG gives photometry parameters, isophotes, luminosity profiles, position angles, and axial ratios at 25 mag arcsec^{-2} in the V band for 791 galaxies brighter than 13 mag selected from the RSA catalog.

PANBG includes 85% of RSA galaxies at $\delta > -25°$. It represents the main part of bright galaxies in the LSC and therefore can be used as a good sample for the study of galaxy orientations in the LSC. The accuracy of the PANBG data has been discussed in section 6.1 (a).

Using this uniform photometry database of galaxies, KO inspected the orientation of SVs of spirals and lenticulars with $cz \leq 3000$ km s^{-1}. They divided the sample into 13 subsamples by the following criteria:

(1) distance from the LSC plane $|SGZ|$;

(2) projected distance r on the LSC plane from the center of the LSC (inner or outer region separation at $r = 10$h^{-1}Mpc);

(3) Virgo cluster membership (galaxies located within a circle of 6° radius centered on M87);

(4) absolute magnitude M_V;

(5) size D (diameter of the major axis); and

(6) morphology T.

Table 1 shows the statistics for the total sample and the subsamples. The 'area' distribution is the number of galaxy SVs which point to 36 sky regions divided in terms of the supergalactic coordinates (L, B). Figure 6 shows the θ and ϕ distributions of SVs of the total sample.

They found the following. Firstly, since all the P($> x_\nu^2$) values for the θ, ϕ, and area distributions of the total sample exceed the critical value 0.050 (Table 1), they concluded that the distribution of SVs of the 618 sample galaxies taken as a whole is isotropic at 95% confidence level.

Secondly, as seen in Fig. 7, the θ distributions of SVs of the $|SGZ|$ subsamples show a tendency that galaxies near the LSC plane tend to have SVs parallel to the LSC plane while those off the LSC plane tend to lay their SVs perpendicular to the LSC plane. They referred to this tendency as the $|SGZ|$ effect. The $|SGZ|$ effect is almost the same effect that Godlowski (1994) found in terms of the supergalactic latitude.

Thirdly, the galaxies in and near the core of the Virgo cluster show a remarkable anisotropy in the ϕ distribution, and the galaxies of the total sample show a similar tendency as well. The projections on the LSC plane of their SVs tend to point to the center of the Virgo cluster, which confirms the claim by MacGillivray and Dodd (1985b). KO found that all of the subsamples shows a dip (more than 1 σ) below those expected from isotropy in $\phi = 0° - 30°$ (over at least two bins), and that more than a 4 σ deviation appears in both 2a (inner region) and 3a (Virgo member) subsamples. In the ϕ distribution of the total sample shown in Fig. 6b, a remarkable dip (2 σ) over 4 bins exists at $\phi = 0° - 40°$ ($\sim$ the direction of SGX axis) at right angles with the direction to the center of the Virgo cluster ($\sim$ the direction of SGY axis). This means that the projections on the LSC plane of SVs of the galaxies tend to point to the Virgo center. In addition to the usually adopted isotropic ϕ distribution (solid line) mentioned above, the expected isotropic distribution with the selection effects taken into account is also shown by the dashed line in Fig. 6b, which was kindly provided by Aryal and Saurer (2004a). Compared with this expected isotropic curve, the dip near $\phi = 0°$ is still clearly visible ($> 1\sigma$). The conclusion on SV projection for the KO total sample is valid even if we consider the selection effects.

7.2 Morphology Dependence of the Virgo Cluster Anisotropy

Galaxy alignments in the Virgo cluster –the core of the LSC– have been well studied by many authors. However, the results derived are quite diverse, and some are even qualitatively inconsistent. Some authors show that the distribution of SVs is random (e.g., Thompson 1976; Hoffman et al. 1989), but others claim that it is anisotropic (e.g., MacGilivary et al.1982; Helou and Salpeter 1982). Even in the anisotropic case, the SVs show an excess in the parallel (e.g., KS) or in the perpendicular (e.g., FG) direction to the LSC plane, or even bimodal (e.g., Adams et al. 1980; KO). These inconsistencies may be due to the difference in sample size, sampling criteria, method and database adopted, and/or accuracy of the data and selection effects, etc. KO analyzed the disk galaxies of the Virgo cluster using the PANBG based on homogeneous surface photometry. However, the total number of their sample galaxies was only 74. Therefore, HWSL made a study of the Virgo Cluster with the new method and a large sample.

The basis of HWSL study was the catalog of 310 disk galaxies in the Virgo cluster compiled by Hu et al. (1993) using the three catalogs, i.e., the catalog of 2096 galaxies in the Virgo cluster region (Binggeli et al., 1985; hereafter VCC), which is based on the large scale (10″.8mm^{-1}) and wide field (2.3 deg^2) photographic survey of the Virgo area by the 2.5-meter du Pond telescope at

Las Campanas, the catalog of groups and group members within 80 Mpc (H_0= 75 km s^{-1} Mpc^{-1})) compiled with the revised hierarchical algorithm (Fouqué et al., 1992; hereafter FGCP), and UGC. The HWSL sample is essentially complete down to a limiting diameter 1.0 arcmin (POSS blue plate) or a limiting magnitude $m = 14.5$ mag for VCC galaxies, and a blue isophotal diameter D$_{25}$ at 25 mag arcsec $^{-2}$ larger than 100 arcsec or an estimated limiting magnitude $m = 14.2$ mag for FGCP galaxies. This data set is the largest one so far, and the corresponding catalog is the largest one ever used in the study of galaxy orientations in the Virgo cluster.

HWSL restricted their sample to disk galaxies and separated the sample galaxies into two broad morphological types, spirals (S) and lenticulars (S0). Morphological types are taken from VCC, which is based on the data of higher image resolution than UGC. PAs are taken from UGC. The diameters and axis ratios, log D_{25} and log R_{25}, are taken from VCC; these values were originally given by de Vaucouleurs and Pence (1979), and Binggeli et al. (1984).

The number of galaxies with/without PA given in UGC is 178/51 for spirals and 67/14 for lenticulars. HWSL extracted from the sample three partially overlapping data sets, SS'E, VCC 6° and VI. The SS'E set contains the member galaxies of S, S' and E clouds of the Virgo I cluster. The VCC 6° set contains all certain and possible VCC cluster members with PA and/or diameters given in UGC which are located within 6° from the cluster center. The VI set consists of the FGCP galaxies belonging to the Virgo I cluster, M group and W cloud.

The θ distributions of SVs of HWSL galaxies with PA given in UGC for S, S0, and S+S0 types are shown in Fig.8a, 8b, and 8c, respectively. It is remarkable that two humps and a dip are seen in all the three panels at nearly the same θ. One of the two humps are at low ($\theta \sim 30° - 50°$) and the other is at high ($\theta \sim 70° - 80°$) ranges, though the high-θ hump is hardly visible in S0. They correspond to excesses of galaxies, with respect to the isotropic distribution, whose SVs tend to be nearly parallel and nearly perpendicular to the LSC plane. The dip is seen at $\theta \sim 0°$. Features of these humps and the dip are summarized in Table 2. HWSL found that the total number of galaxies responsible for the dip was roughly equal to the number of galaxies without PA given in UGC for all the cases. When they assigned random values to PAs of those galaxies without PA but with diameters given in UGC, the two humps remained essentially unchanged while the dip almost disappeared leaving a remnant narrow dip at $\theta < 10°$ as shown in Fig.9 for the data set VI. This remnant dip can be understood as the result of the selection effect of the Virgo cluster from the results of the simulation (see Fig.6a for the spirals (VI); Aryal and Saurer, 2000).

In summary, HWSL found that the distribution of SV orientations of disk galaxies in the Virgo cluster shows anisotropy in the θ distribution, and that there is also a discernible anisotropy in the ϕ distribution in the sense that projection onto the LSC plane of SVs tends to point to the center of the Virgo cluster. Earlier findings by MacGillvray and Dodd (1985b) and KO are confirmed. HWSL also showed that the anisotropy is dependent on morphology. Spirals show two humps in both the high and low-θ ranges while lenticulars show the low-θ hump only. This indicates that lenticulars show little excess of SVs perpendicular to the LSC plane. In the ϕ distribution, the dip near the direction perpendicular to the center of the Virgo cluster appears to be deeper for lenticulars than for spirals. This means that the effect of SVs pointing towards the center of the Virgo cluster may be more pronounced for lenticulars than for spirals.

Note that Wu et al. (1997, 1998) found a similar morphology dependence in the Coma cluster (a rich cluster of galaxies) as that found in the Virgo cluster (a loose cluster of galaxies), suggesting that the morphology dependence of the orientation of disk galaxies in clusters is independent of the richness of clusters (Hu et al., 1996).

7.3 'Field' Galaxies as the Probe of Formation Epoch

Fuller, West, and Bridges (1999) showed that the brightest galaxies in some poor clusters, like their counterparts in richer Abell clusters, are preferentially aligned with the principal axes of their host clusters as well as the surrounding distribution of nearby Abell clusters. They suggested that these alignments, independent of cluster richness, are most likely produced by formation of the brightest cluster galaxies by anisotropic infall along filamentary structures.

However, galaxies in the high-density regions of clusters or superclusters may not be the best objects to probe the condition at the formation epoch because the post-formation dynamical effects such as merging, tidal effects, and other gravitational effects can disturb the original distribution of galaxy orientations.

The fact that the SVs of galaxies in the Virgo cluster tends to point to the cluster center (e.g., MacGillivray and Dodd, 1985b; KO, and HWSL) may be evidence for such dynamical effects. Galaxies in low-density regions in the LSC, i.e. those which do not belong to any cluster or group may preserve the fossil nature of the SV orientations better. We will refer to these as 'field' galaxies. It is interesting to see whether the morphology dependence of the orientation of disk galaxies found in Virgo cluster also exists in field galaxies.

The samples studied by KO included the members of groups and clusters. Hu et al. (1998; hereafter HYSWL) constructed a new sample of bright field disk galaxies in the LSC from the PANBG database by rejecting the members of groups which consist of more than three members (Fouqué et al., 1992). This sample comprised 220 field disk galaxies brighter than 13th mag and radial velocities $V \leq 3000$ km s^{-1}. HYSWL divided the sample into four subsamples according to morphology; S0, Sa-bc, Sc-m, and Sa-m. Table 3 shows their results of χ^2 test for θ, ϕ and 'area' distributions. The θ distributions of the subsamples are presented in Fig. 10.

HYSWL found the following. Firstly, the orientations of SVs of the field disk galaxies are significantly different from those of 618 PANBG disk galaxies as a whole in both the θ and ϕ distributions. The distribution of the SVs of field galaxies(total sample) shows a weak tendency parallel to the LSC plane. It is worthwhile to mention that, if we take into account the selection effect pointed by Aryal and Saurer (2000), the projections of SVs of the field galaxies (total sample) onto the LSC plane are isotropic (see Fig. 5a). This is completely different from the cases of the LSC as a whole (e.g., total sample of KO), and the Virgo cluster (e.g., KO and HWSL)

Secondly, the distribution of SV orientations of the field disk galaxies is also morphology dependent. Lenticulars, which shows the most concentrated spatial distribution toward the LSC plane, i.e., with the smallest mean $|SGZ|$ value, show a significantly anisotropic distribution of orientations. Their SVs tend to align parallel to the LSC plane. Spirals, on the other hand, in general do not show any significant alignment of their SVs with the LSC plane. Fig. 10 shows clearly that the distribution of SVs is anisotropic for lenticulars while it is isotropic for spirals. This is confirmed by the the results of χ^2 test of θ distribution given in Table 3.

Third, the $|SGZ|$ effect claimed by KO is confirmed for field galaxies. It may be largely due to the morphology dependence.

Based on these results, HYSWL suggested that lenticulars and spirals might have different formation processes, and that field galaxies might therefore be a better probe to detect information about the formation of the LSC in the early universe.

The results of χ^2 tests of the θ and ϕ distributions are somewhat dependent on the bin size. Yuan et al. (2000) used the K-S test to re-examine the SV distributions of all the samples analyzed by HYSWL. They confirmed the results of HYWSL that the θ distribution of the field spirals is isotropic while that of the field lenticulars is anisotropic. The bin size of 10° adopted by HYSWL gave the same results as K-S test in the statistical sense. The K-S test also revealed that the field spirals (Sa-bc galaxies) and lenticulars (S0) do not originate from the same parent distribution at the 96.83 % confidence level.

Yuan et al. (1997) constructed another sample of 302 galaxies within the LSC by rejecting the members of groups with at least five members. For this sample, the θ distribution of neither lenticulars nor spirals shows a tendency for the SVs to be parallel to the LSC plane. The χ^2 test of θ distribution confirms that spirals and lenticulars show an isotropic distribution, a result different from HYSWL. This suggests that the θ distribution of field disk galaxies is sensitive to the criteria for field galaxies.

7.4 Discussion

The spatial orientation of disk galaxies in superclusters may give us some clues on the formation processes at an early stage of their formation. The distribution of SVs of the field disk galaxies is significantly different from that of cluster member galaxies. This suggests that cluster member galaxies suffered dynamical effects after formation, and changed their spin orientations collectively.

Field disk galaxies show a weak morphology-dependent tendency to have their SVs parallel to the LSC plane. Lenticulars show a strong tendency, while spirals do not show such tendency. The isotropic feature in the θ distribution of SVs of the spirals looks to support the classical bottom-up (or CDM) model, i.e., gravitationally hierarchical clustering formation scenario of the LSC. On

the other hand, the anisotropic distribution for lenticulars, which are spatially more concentrated towards the LSC plane, is apparently consistent with the prediction of the classical 'pancake' model.

The tendency that lenticulars lay their SVs parallel to the LSC plane was also observed for samples other than the HYSWL sample which consisted of PANBG field lenticulars. It was found, as the $|SGZ|$ effect, for a sample of 289 galaxies near the LSC plane extracted from 618 PANBG galaxies (KO). As we already mentioned, there are also several independent studies of galaxy alignment in the LSC not based on PANBG which show a similar tendency, e.g., 1275 UGC galaxies with radial velocities smaller than 2600 km s^{-1} (FG); 2227 UGC and ESO/U galaxies with radial velocities smaller than 2600 kms^{-1} and another independent sample from the NBG catalog (Goldlowski, 1993, 1994). We therefore conclude that the tendency of lenticulars to have their SVs parallel to the LSC plane has a firm observational basis.

In order to understand the morphological dependence of orientation of the bright isolated disk galaxies in the LSC, a morphology-dependent hybrid theory of galaxy formation might have to be invoked. At this point, however, we should keep in mind that the results of orientation of the PANBG field galaxies as discussed in HYSWL is based on only 220 field disk galaxies in the LSC. More observations are necessary to confirm the results of the PANBG field galaxies.

8   Summary and Prospects

Progress has been made during the past decades in studying the distribution of orientations of galaxies in the LSC :

1. The method used was upgraded from a two-dimensional analysis, i.e. the analysis of the distribution of position angles and/or the distribution of axial ratios independently, to a three-dimensional analysis, where we analyze the direction of the spin vector (the normal to the galaxy plane) by taking account of both the position angle and axial ratio simultaneously. In the three-dimensional analysis, however, there are four possible solutions regarding the orientation of the SV of a galaxy with a given position angle and a given axial ratio. This ambiguity is caused by the fact that we do not know which side of the galaxy is closer to us. The availability of HI velocity fields removes this ambiguity. However, there is not yet a large sample of LSC galaxies with such data.

2. The advent of the Uppsala General Catalogue of Galaxies (UGC) and the ESO/Uppsala Survey of the ESO(B) Atlas (ESO/U) stimulated the research in this field. Based on homogeneous surface photometry of galaxies, the Photometric Atlas of Northern Bright Galaxies (PANBG) provided a database for further studies of the orientations of bright galaxies in the LSC.

3. Selection effects on the location of galaxies on the sky and on the inclination angle often play an important role. Proper simulations should be made to interpret the results.

4. When the LSC is seen as a whole, galaxy planes tend to align perpendicular to the LSC plane, i.e. their spin vectors are aligned parallel to the LSC plane. The projections of spin vectors onto the LSC plane tend to point to the Virgo cluster center. There is evidence indicating that these tendencies are dependent on morphology, with lenticulars showing the most significant effect. The $|SGZ|$ effect of galaxy orientation found for the PANBG galaxies of the LSC is mostly due to this morphology dependence and to the fact that lenticulars are spatially more concentrated toward the LSC plane than spirals.

5. Projections of the spin vectors onto the LSC plane of Virgo cluster member galaxies, and those of the total LSC sample, tend to point to the Virgo cluster center. The effect is more pronounced for lenticulars than for spirals. This suggests that member galaxies of the Virgo cluster may have experienced the post-formation dynamical effects.

6. 'Field' galaxies, i.e., those which do not belong to groups with more than three members, might be better objects to search for information about the epoch of galaxy formation. Orientations of spin vectors of the 220 field disk galaxies are significantly different from those

of 618 PANBG disk galaxies as a whole. The θ distribution of SVs is anisotropic for field lenticulars while it is isotropic for field spirals. Field lenticulars exhibit a clear trend to have their spin vectors parallel to the LSC plane.

It is important to increase the sample size of LSC galaxies, especially 'field' LSC galaxies, available to the analysis. HYSWL used only 220 PANBG field galaxies (selected by $cz \leq 3000$ km s^{-1}) brighter than 13 mag. Going deeper by one magnitude with relevant velocity information would result in a significant increase. Accurate position angles and axial ratios derived by surface photometry are essential to obtain reliable results. The use of the non-parametric KS test would also improve the analysis.

Up to now no study has used homogeneous data covering both northern and southern hemisphere for galaxies of the LSC. It is attractive to extend PANBG, a database based on homogeneous surface photometry of bright galaxies with $\delta > -25°$, to southern hemisphere to form a whole sky complete sample of bright galaxies in the LSC. Using existing databases to extend the study of the PANBG field galaxies to cover the whole sky may be an alternative way ahead in this regard.

The Westerbork Survey of HI in Spiral Galaxies (WHISP) is carrying out observation of the distribution and velocity structure of neutral hydrogen in several hundred bright spiral galaxies. These data will be of great help in resolving the degeneracy of the orientations of the spin vector and will provide us with a powerful database for a research on the orientations of bright spirals in the LSC.

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Table 1. Statistics for the total sample and the subsamples (Kashikawa and Okamura, 1992).[1]

		N	x_ν^2	θ (9bins) P($> x_\nu^2$)	x_ν^2	ϕ (18bins) P($> x_\nu^2$)	x_ν^2	area(36bins) P($> x_\nu^2$)
	Total sample	618	1.910	0.054	1.441	0.106	1.113	0.297
	Subsamples							
(1)-1a	$|SGZ| < 2h^{-1}$ Mpc	289	2.543	0.009*	0.787	0.710	0.909	0.621
-1b	$|SGZ| \geq 2h^{-1}$ Mpc	329	2.114	0.031*	1.015	0.438	1.211	0.183
(2)-2b	Inner region	292	0.871	0.541	1.687	0.038*	1.831	0.002*
-2b	Outer region	326	2.014	0.041*	0.632	0.870	0.809	0.779
(3)-3a	Virgo member	74	2.444	0.012*	2.784	0.000*	1.657	0.009*
-3b	Non-member	544	2.379	0.015*	0.925	0.544	0.947	0.556
(4)-4a Mag.	$Mv < -19 + 5\log h$	338	2.730	0.005*	1.307	0.176	1.029	0.422
-4b	$Mv \geq -19 + 5\log h$	280	0.779	0.622	0.824	0.667	1.123	0.284
(5)-5a Size	$D < 7h^{-1}$ Kpc	276	1.040	0.403	1.101	0.345	1.087	0.333
-5b	$D \geq 7h^{-1}$ Kpc	342	3.648	0.000*	1.276	0.197	1.176	0.220
(6)-6a Morph.	$T = -3 - -1$	122	1.186	0.303	0.887	0.590	1.627	0.011*
-6b	$T = 0 - 4$	271	3.659	0.000*	1.000	0.454	1.024	0.430
-6c	$T = 5 - 10$	225	0.311	0.962	0.800	0.695	1.211	0.183

1) N is the number of sample. Asterisks mark the P($> x_\nu^2$) value which is smaller than the critical value (0.05), indicating the anisotropic distribution.

Table 2. The θ distribution of SV of galaxies of the Virgo cluster. (Hu et al., 1995)

morphological type		(1)dip at $\theta \sim 0°$	(2)hump at low θ	(3)hump at high θ
spirals (S)	θ range	$0° - 30°$	$30° - 50°$	$70° - 80°$
	Deviation	$\sim 3\sigma$	$\sim 1 - 2\sigma$	$\sim 1 - 2\sigma$
lenticulars (S0)	θ range	$0° - 10°$	$20° - 50°$	
	Deviation	$> 4\sigma$	$\sim 1 - 2\sigma$	
S+S0	θ range	$0° - 20°$	$30° - 50°$	$70° - 80°$
	Deviation	$> 4\sigma$	$\sim 2 - 3\sigma$	$\sim 1 - 2\sigma$

Table 3. The results of χ^2 test of θ, ϕ, and area distribution (Hu et al., 1998).

Data sets and T selection	N	$< |SGZ| >$	χ_ν^2	θ (9 bins) P($> \chi_\nu^2$)	χ_ν^2	ϕ (18 bins) P($> \chi_\nu^2$)	χ_ν^2	Area (36 bins) P($> \chi_\nu^2$)
S0(-3$\leq T \leq$0)	41	4.25 $h^{-1}Mpc$	2.231	0.023[b]	1.736	0.030[b]	1.514	0.026[b]
Sa-bc(1$\leq T \leq$4)	84	7.31	0.768	0.631	1.992	0.009[b]	1.537	0.022[b]
Sc-m(5$\leq T \leq$9)	90	5.56	0.900	0.510	2.106	0.005[b]	1.519	0.025[b]
Sa-m(1$\leq T \leq$9)	174	6.40	1.341	0.218	3.426	0.000[b]	2.218	0.000[b]
Total(-3$\leq T \leq$10)	220	5.91	1.255	0.262	4.520	0.000[b]	2.932	0.000[b]

[b] : P($> \chi_\nu^2$) < 0.05 is regarded as the anisotropic distribution.
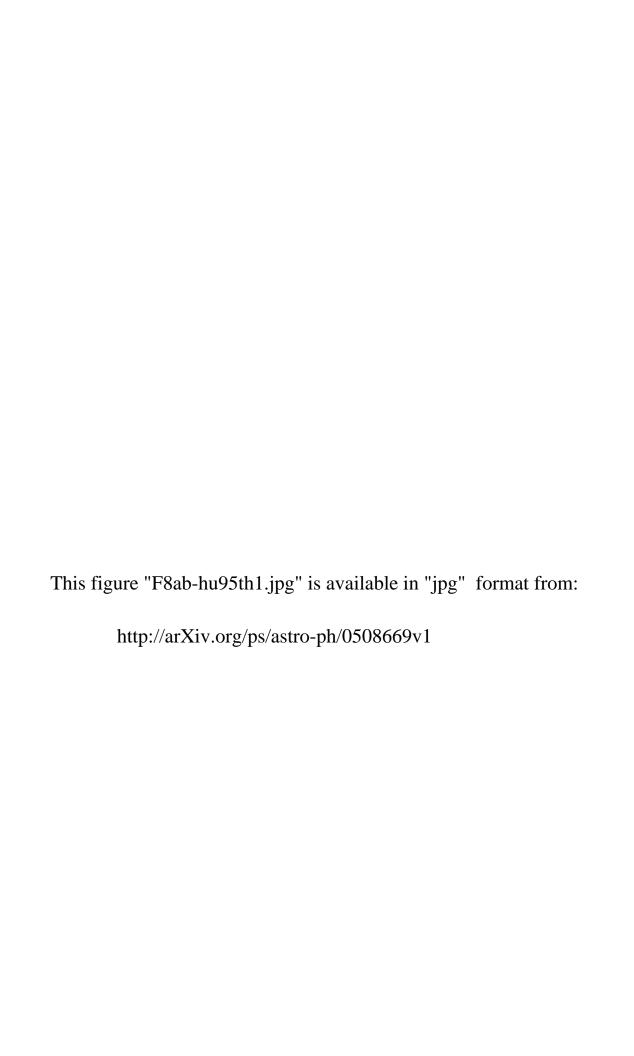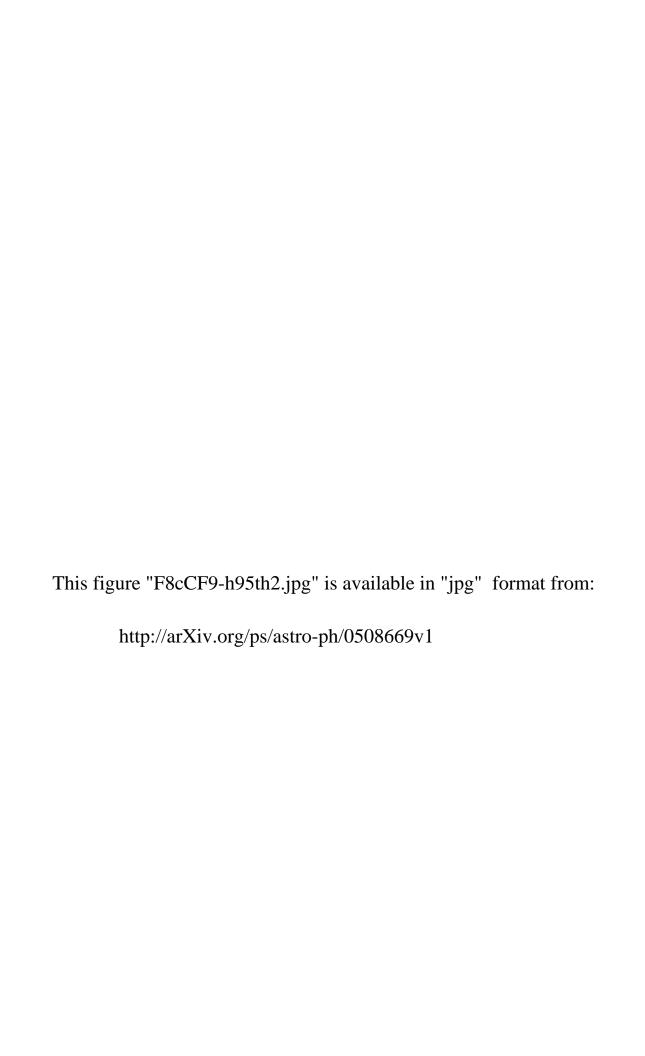
Figure Captions

Fig.1. Schematic illustration of angles θ and ϕ which defines the orientation of the spin vector of a galaxy in the LSC. L and B are the supergalactic coordinates. SGX is directed towards the point L=0°, B=0°, and the SGZ towards the north super-galactic pole, B=+90°. SGX and SGY are in the LSC plane. Angle θ is the polar angle between the galaxy spin vector and the LSC plane. Angle ϕ is the azimuthal angle between the projection on the LSC plane of the galaxy spin vector and the SGX-axis. The hatched ellipse represents a projection of the galaxy shape onto the sky, which we observe. Angle P is the position angle in the supergalactic coordinate. (Kashikawa and Okamura, 1992)

Fig.2. The observed (solid line) and the theoretical (dashed line) isotropic distributions of the angle δ (a), and angle η (b) for the whole sample of galaxies. (Godlowski, 1994)

Fig.3. Comparison of the axial ratio and the position angle between UGC and PANBG for 387 galaxies. (a) b/a(UGC) versus b/a(PANBG), and (b) PA(PANBG)$-PA$(UGC) versus b/a(PANBG). (Kashikawa and Okamura, 1992)

Fig.4. The number of galaxies versus the inclination angle i of 310 disk galaxies in the Virgo area with PA and/or diameters given in UGC. The inclination angle i was estimated from $\log R_{25}$, the major to minor axial ratio at 25 B mag arcsec $^{-2}$ taken from Binggeli et al. (1985), assuming the intrinsic axial ratio $q_0 = 0.2$. The number of galaxies with UGC PA (dash line), those with UGC diameters but without UGC PA (dotted line), and the total (solid line) are shown. (Hu et al., 1993).

Fig.5 (a) The θ distribution of the spirals (the VI set) of the Virgo cluster. A random distribution of PAs is assumed for the galaxies without PA given in UGC (HWSL); (b) The ϕ distribution of the field galaxies (the total sample; HYSWL). In both panels, the solid lines are the expected isotropic distributions resulted from the simulations by Aryal and Saurer (2000) while the dashed lines are isotropic distributions without any selection effects taken into account.

Fig.6. The θ distribution (a), and ϕ distribution (b) of the total sample of (Kashikawa and Okamura, 1992). Statistical 1σ error bars and the isotropic distribution without any selection effect is shown by the solid line. $\phi = 0°$ corresponds to +SGX direction. The expected isotropic distribution with the selection effects taken into account is shown by the dashed line in panel (b), which was kindly provided by Aryal and Saurer (2004a).

Fig.7 The θ distributions of the subsamples of (Kashikawa and Okamura, 1992): (1a) $|SGZ| < 2h^{-1}$Mpc, (1b) $|SGZ| \geq 2h^{-1}$Mpc. Statistical 1σ error bars are shown. The solid lines are the isotropic distributions without any selection effect.

Fig.8. The θ distributions of SVs of lenticulars (a), spirals (b) and lenticulars plus spirals (c) with PA given in UGC for various data sets of the Virgo cluster. The isotropic distribution without any selection effect is shown by the solid line. Statistical 1σ error bars are indicated. (Hu et al.,1995)

Fig.9. The θ distributions of SVs of lenticulars (a), spirals (b) and lenticulars plus spirals (c) (Set VI) of the Virgo cluster when random values are assigned to PAs of those galaxies without PA given in UGC. (Hu et al., 1995).

Fig.10. The θ distributions of SVs of the 'field' galaxies for S0(a), Sa-bc(b), Sc-m(c), and Sa-m(d) subsamples. Statistical 1σ error bars are shown. The solid lines are the isotropic distributions without any selection effect. (Hu et al., 1998).

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